Searching the Relaxion at Particle Accelerators

Martin W. Winkler

Phys. Lett. B727 (2013), Rept. Prog. Phys. 79 (2016)
& work in progress

NORDITA

PLANCK 2017
Warsaw, May 25, 2017

Stockholm University

Light Scalar Mixing with the Higgs

- simplest extension of SM: one singlet scalar

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{2}(\partial\phi)^2 - \frac{1}{2}m^2\phi^2 + A\phi h^2 + \ldots$$

- mixing with the Higgs induces coupling to SM fields

$$\mathcal{L} \supset s_\theta \; y_f \bar{f} f$$

universal suppression

- considered mass range $m_\phi = 0.1 - 10\,\mathrm{GeV}$

Motivation: Relaxion

- relaxion potential

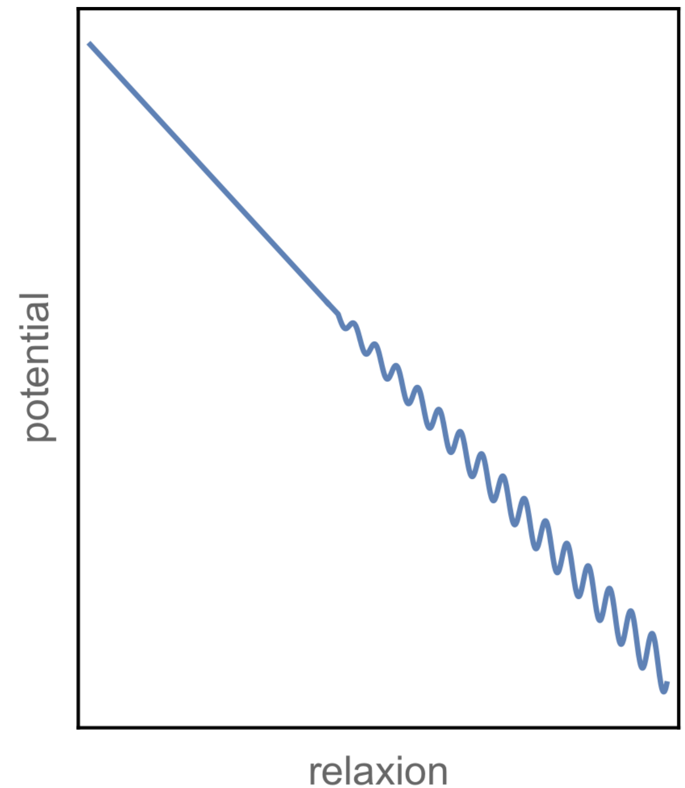
Graham, Kaplan, Rajendran, Phys. Rev. Lett. 115 (2015)

$$V = \left(M^2 - Mg\phi\right) h^2 - M^3 g\phi$$

Higgs mass **relaxion slope**

$$+ \Lambda^2 h^2 \cos\left[\frac{\phi}{f}\right] + 3H^2$$

barrier potential **dissipation**



- electroweak scale

$$\Rightarrow \langle h \rangle^2 \sim g \frac{M^3 f}{\Lambda^2}$$ unless $H < m_\phi$

- relaxion properties

$$m_\phi \sim \frac{\Lambda m_h}{f} \qquad s_\theta \sim \frac{f\, m_\phi^2}{m_h^3} \;\mathrm{Min}\left[1, \frac{H}{m_\phi}\right]$$

see also:
Choi, Im, JHEP 1612,
Flacke et al., arXiv:1610.02025

Accelerator Window

- severe constraints on inflationary sector

$$H \lesssim m_h \qquad\qquad e-\text{folds} \gtrsim \frac{f^2\,H^2}{\Lambda^4}\,\frac{M^4}{m_h^4}$$

  alleviated for Λ, f close to weak scale

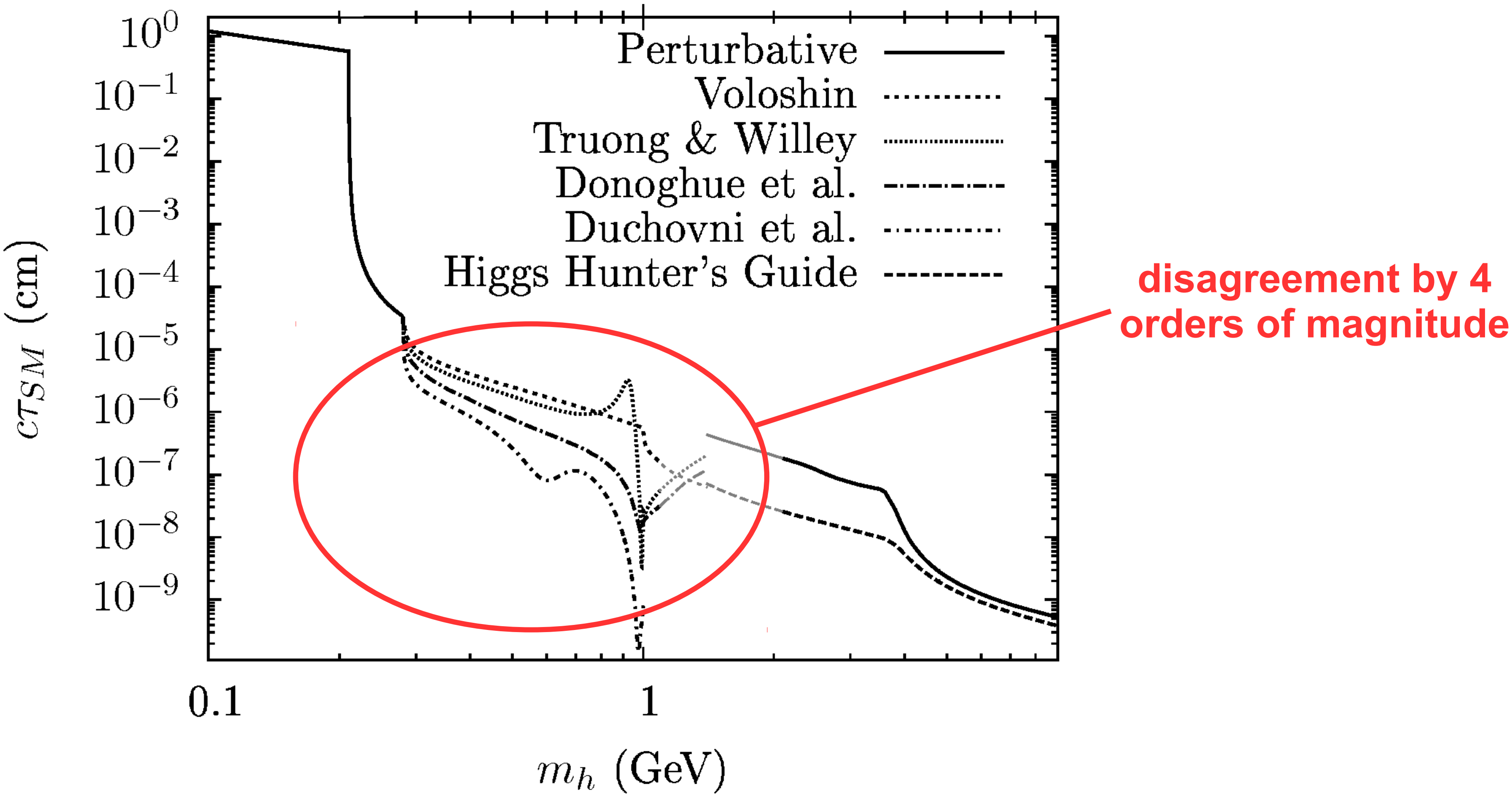
$$\Rightarrow\ m_\phi \sim 0.1 - 10\,\mathrm{GeV}$$

- light scalar also appears as mediator in dark matter models
  Kappl, Ratz, M.W. (2011)

- inflation models with light inflaton
  Bezrukov, Gorbunov, JHEP 1005 (2010)

Scalar Decay

- large theoretical uncertainties on scalar decay



Clarke, Foot, Volkas, JHEP 1402 (2014)

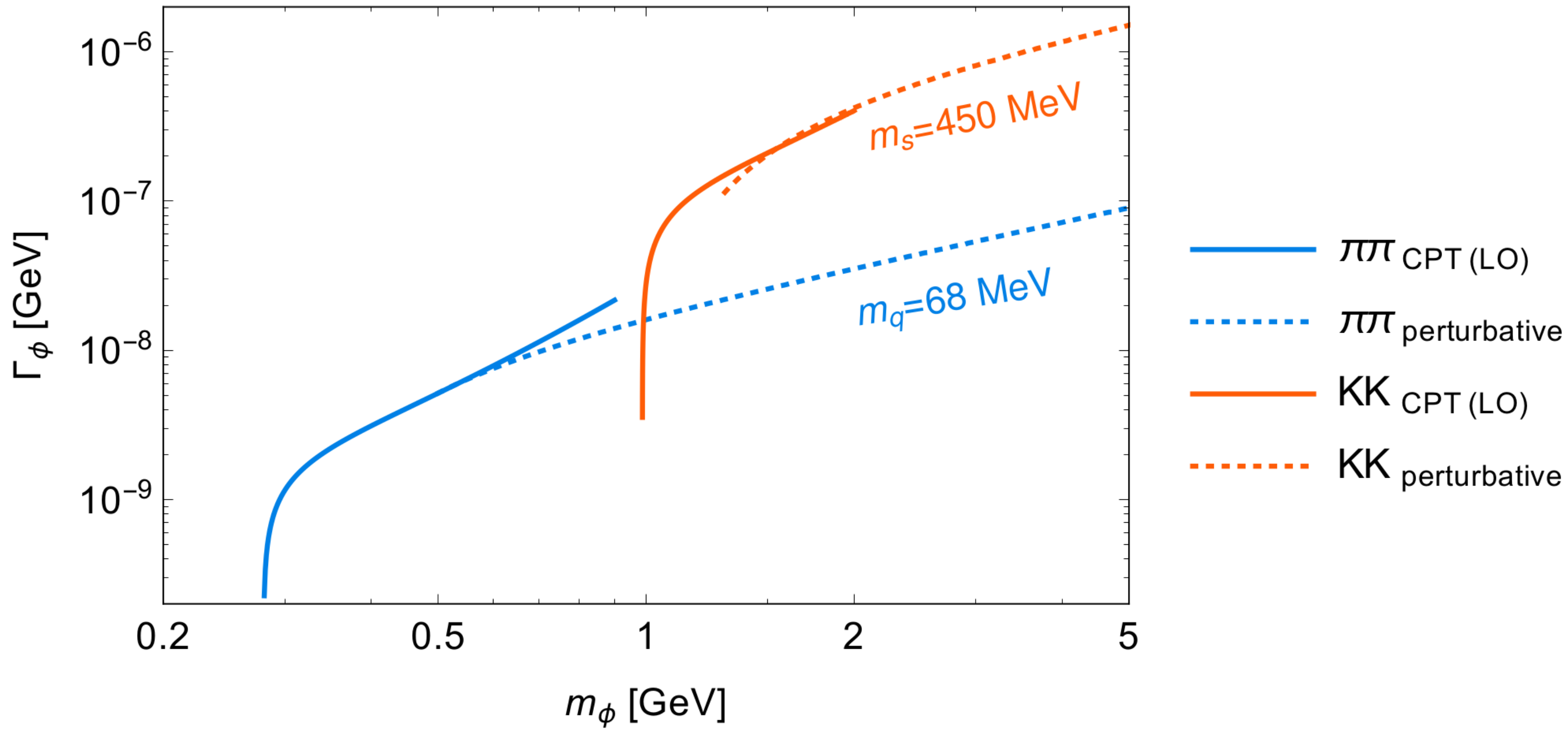
Chiral Perturbation Theory

- decay rate of ϕ

$$\Gamma_{ff} \propto s_\theta^2\, G_F\, m_\phi m_f^2 \quad \text{(perturbative)}$$

$$\Gamma_{\pi\pi} \propto s_\theta^2 \frac{G_F}{m_\phi} \left| \left\langle \pi\pi \left| \tfrac{2}{7}\Theta^\mu_\mu + m_u \bar{u}u + m_d \bar{d}d + m_s \bar{s}s \right| 0 \right\rangle \right|^2$$

Voloshin, Sov.J.Nucl.Phys. 44 (1986)



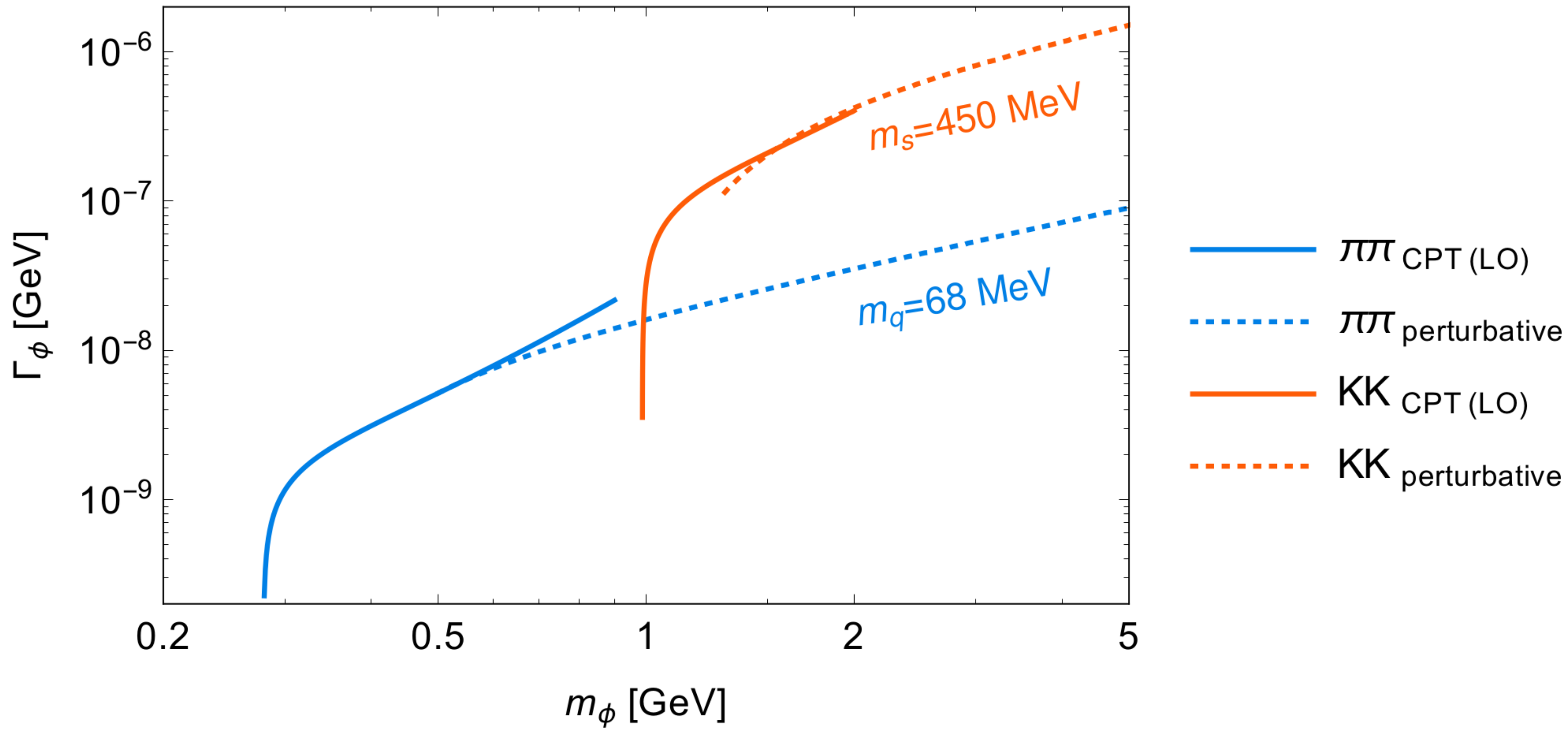
Chiral Perturbation Theory

- decay rate of ϕ

$$\Gamma_{ff} \propto s_\theta^2\, G_F\, m_\phi m_f^2 \quad \text{(perturbative)}$$

$$\Gamma_{\pi\pi} \propto s_\theta^2 \frac{G_F}{m_\phi} \left|\left\langle \pi\pi \left| \tfrac{2}{7} m_\phi^2 + \tfrac{11}{7} m_\pi^2 + \mathcal{O}\left(m_{\phi,\pi}^4\right) \right| 0 \right\rangle\right|^2$$

Voloshin, Sov.J.Nucl.Phys. 44 (1986)



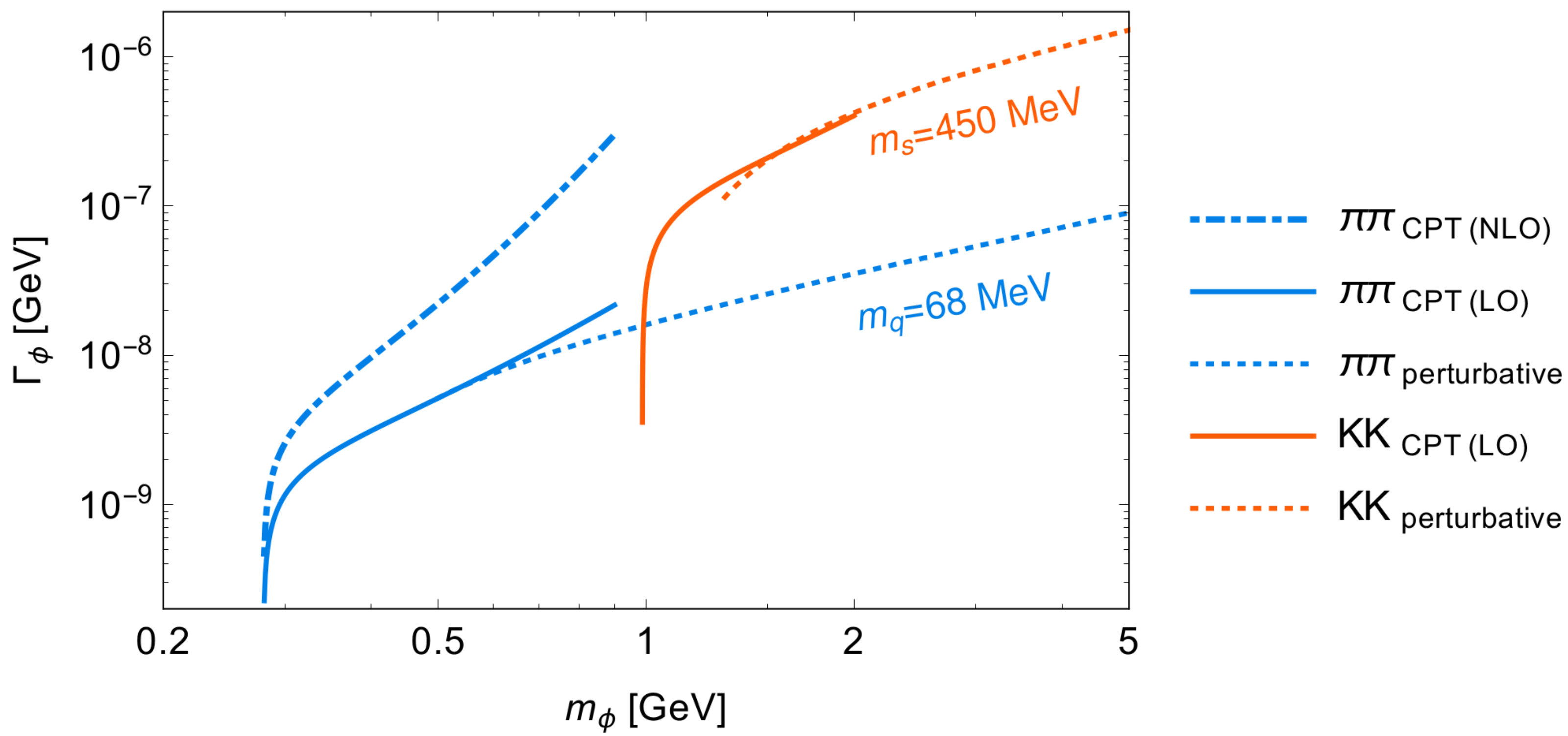
Chiral Perturbation Theory

- decay rate of ϕ

$$\Gamma_{f\,f} \propto s_\theta^2\, G_F\, m_\phi m_f^2 \quad \text{(perturbative)}$$

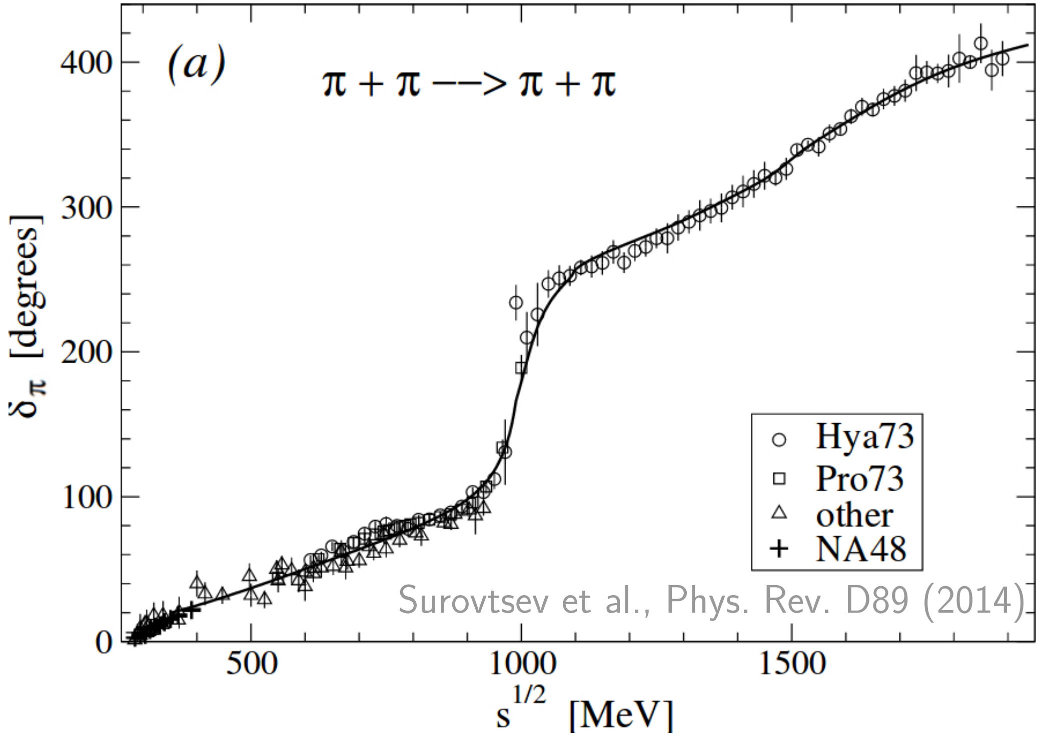
$$\Gamma_{\pi\pi} \propto s_\theta^2 \frac{G_F}{m_\phi} \left|\left\langle \pi\pi \,\middle|\, \tfrac{2}{7} m_\phi^2 + \tfrac{11}{7} m_\pi^2 + \mathcal{O}\left(m_{\phi,\pi}^4\right) \middle|\, 0 \right\rangle\right|^2$$

Voloshin, Sov.J.Nucl.Phys. 44 (1986)



Phase Shift Analysis

- extract form factors from $\pi\pi$ phase shift data
  Raby, West, Phys.Rev. D38 (1988), Truong, Willey Phys.Rev. D40 (1989), Donoghue, Gasser, Leutwyler, Nucl.Phys. B343 (1990)



Surovtsev et al., Phys. Rev. D89 (2014)

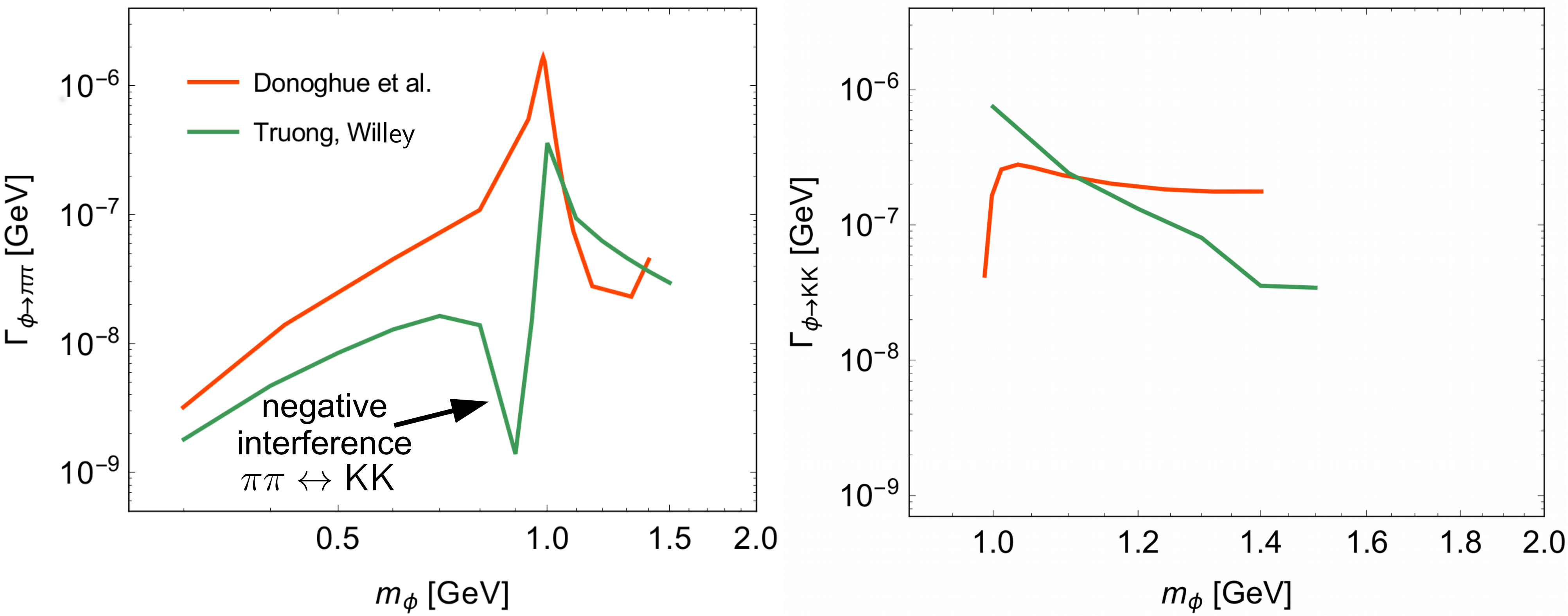
$$\left\langle \pi\pi \left| \Theta^{\mu}_{\mu} \right| 0 \right\rangle = \mathrm{P(s)} \exp\left[\frac{\mathrm{s}}{\pi} \int \frac{\mathrm{dt}}{\mathrm{t}} \frac{\delta_\pi(\mathrm{t})}{\mathrm{t-s}} \right]$$

Omnes, Nuovo Cimento 8 (1958)

- generalized to two-channel analysis to include KK
  Muskhelishvili (1965)

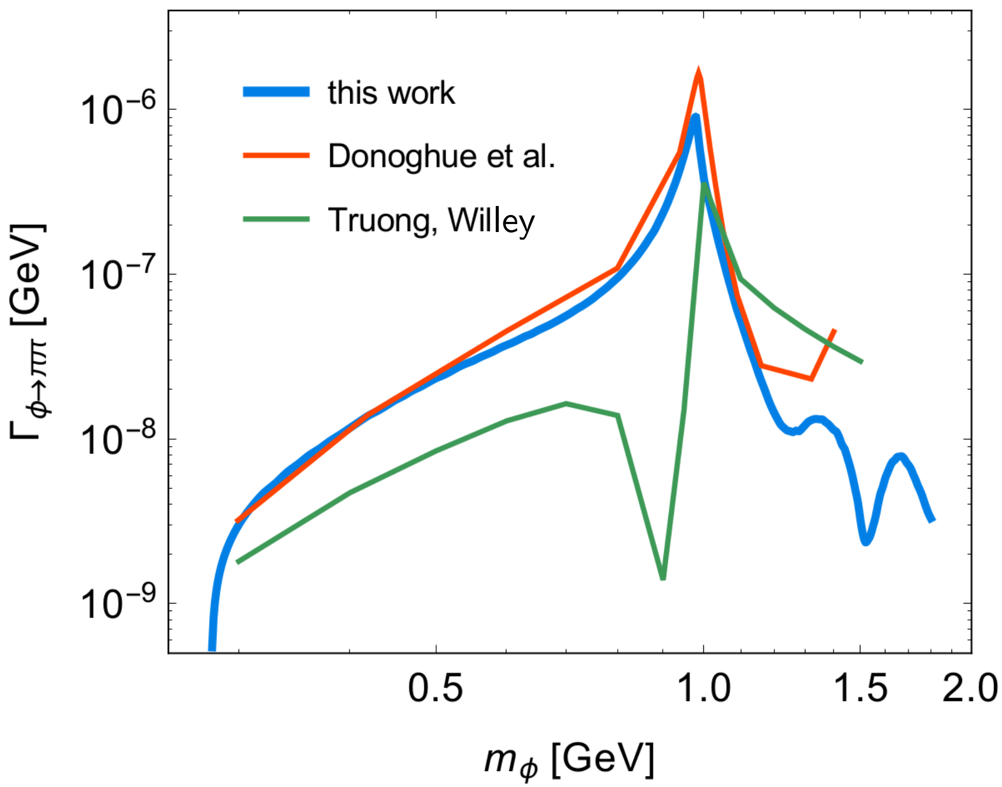
Phase Shift Analysis

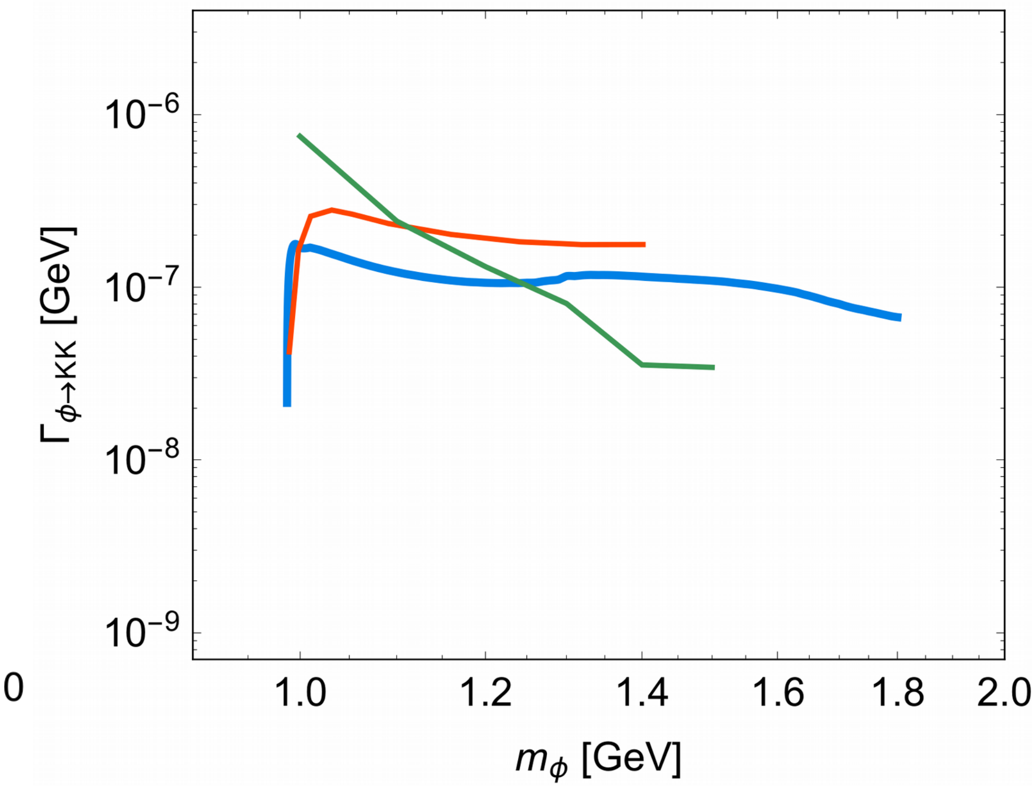
- disagreement Trung, Willey vs. Donoghue et al.



Phase Shift Analysis

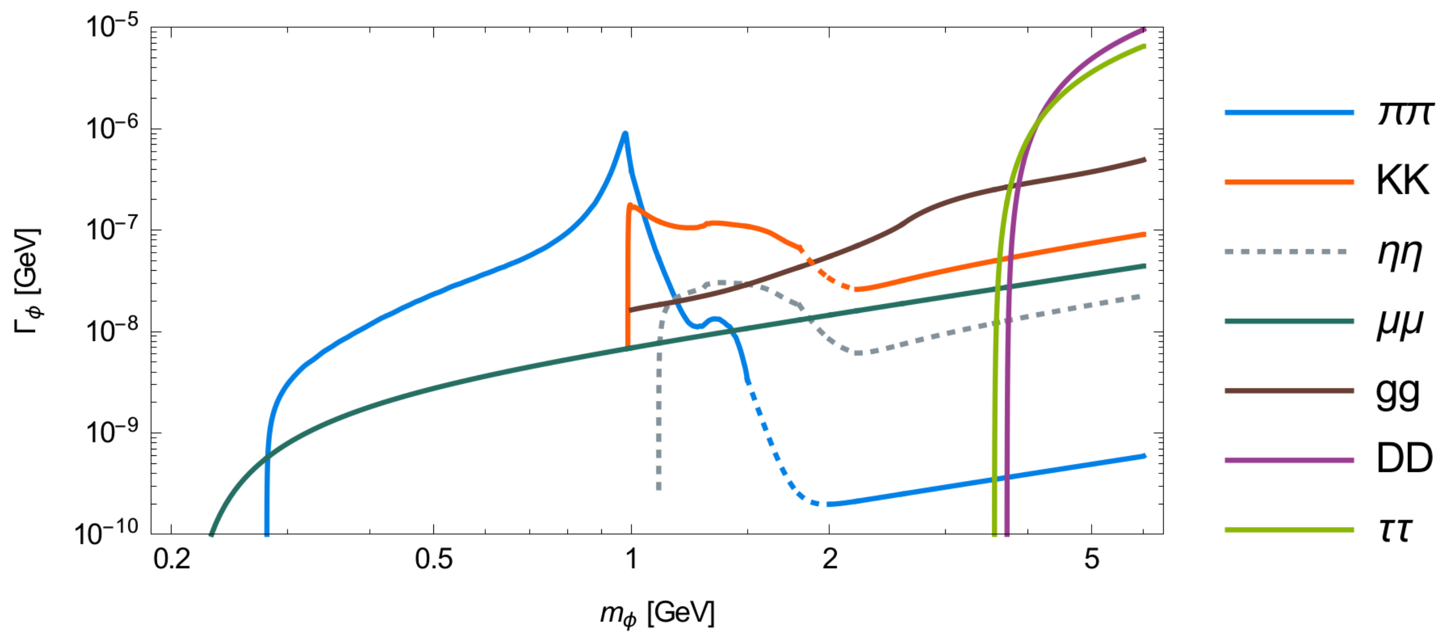
- disagreement Trung, Willey vs. Donoghue et al.

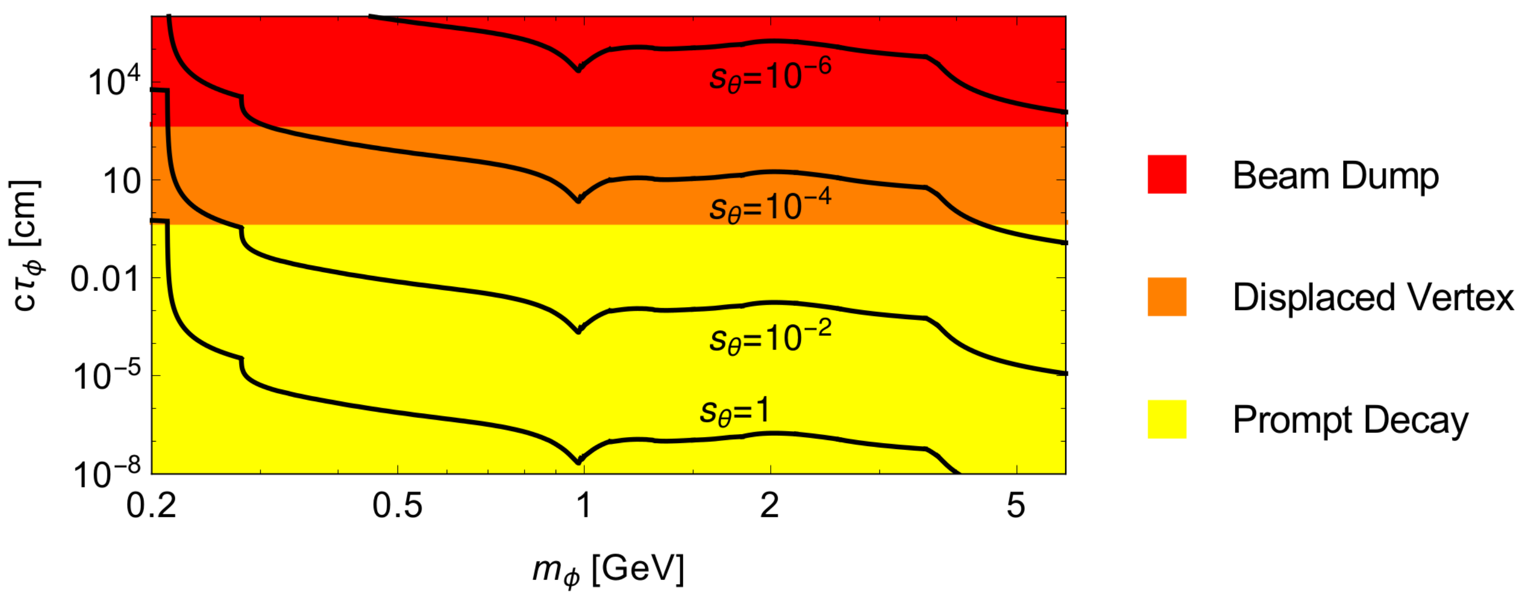




- we recalculated decay rates based on phase shift analysis by Hoferichter et al. JHEP 1206 (2012)

Decay Pattern

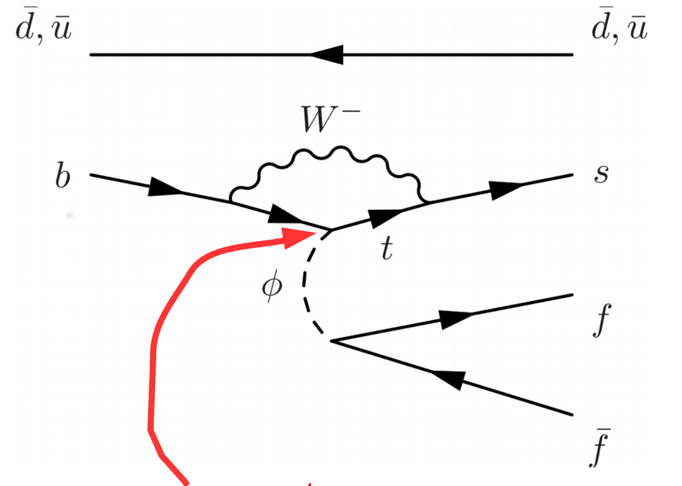




Rare Decays at LHCB

- rare meson decays provide very sensitive probe

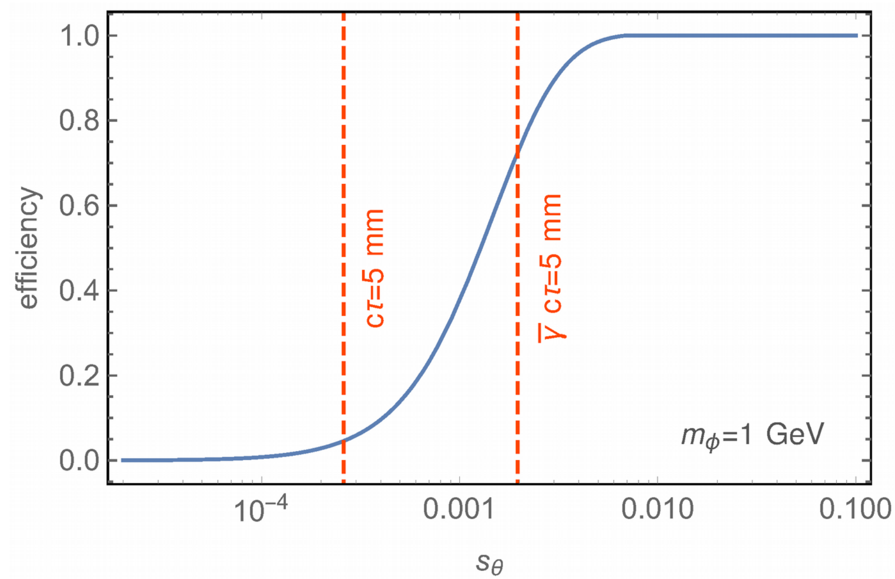
$$B \rightarrow K + \phi$$
$$K \rightarrow \pi + \phi$$
$$\Upsilon \rightarrow \gamma + \phi$$



$$s_\theta \frac{G_F^{3/2}\, m_b\, m_t^2\, V_{ts}^* V_{tb}}{16\pi^2}$$

- LHCB search for $B \rightarrow K\mu\mu$
  JHEP 1302 (2013)

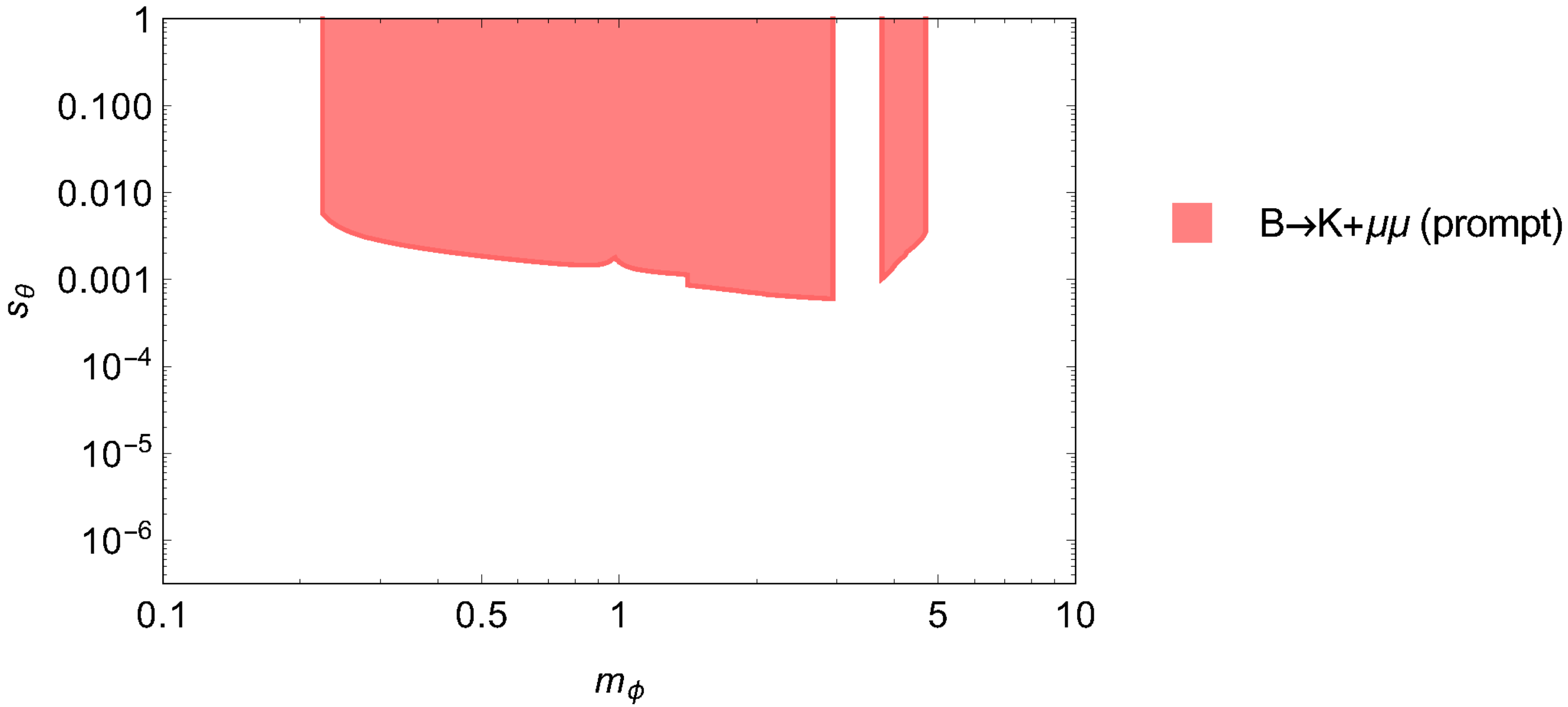
  not optimized for light scalar (vertex cuts)



- new searches for B decays to long-lived boson

$B \to K^{(*)}\mu\mu$ (LHCB) $B \to X_s\, \pi\pi, KK$ (BaBar)

Phys.Rev.Lett. 115 (2015), Phys.Rev. D95 (2017) Phys. Rev. Lett. 114 (2015)

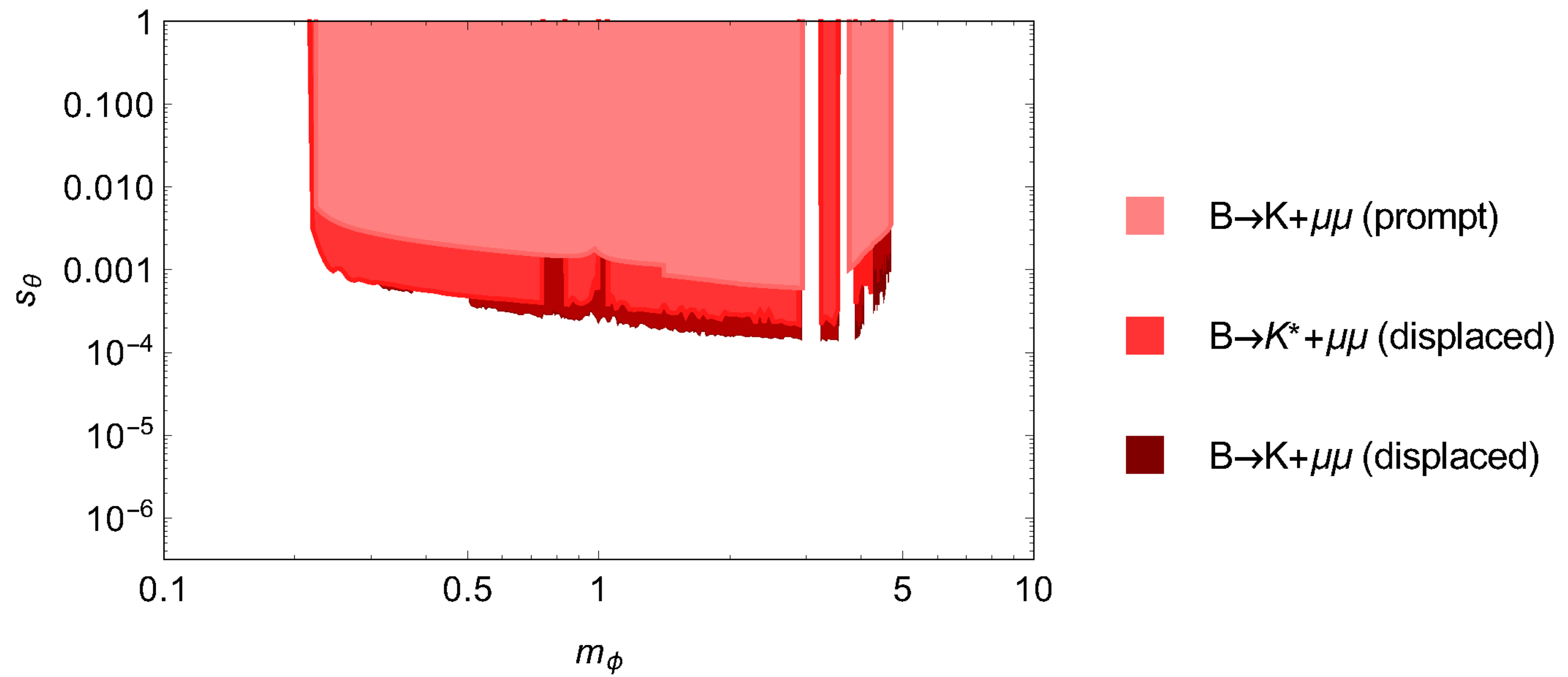


Displaced Vertices

- new searches for B decays to long-lived boson

$B \to K^{(*)}\mu\mu$ (LHCB) $B \to X_s\, \pi\pi, KK$ (BaBar)

Phys.Rev.Lett. 115 (2015), Phys.Rev. D95 (2017) Phys. Rev. Lett. 114 (2015)

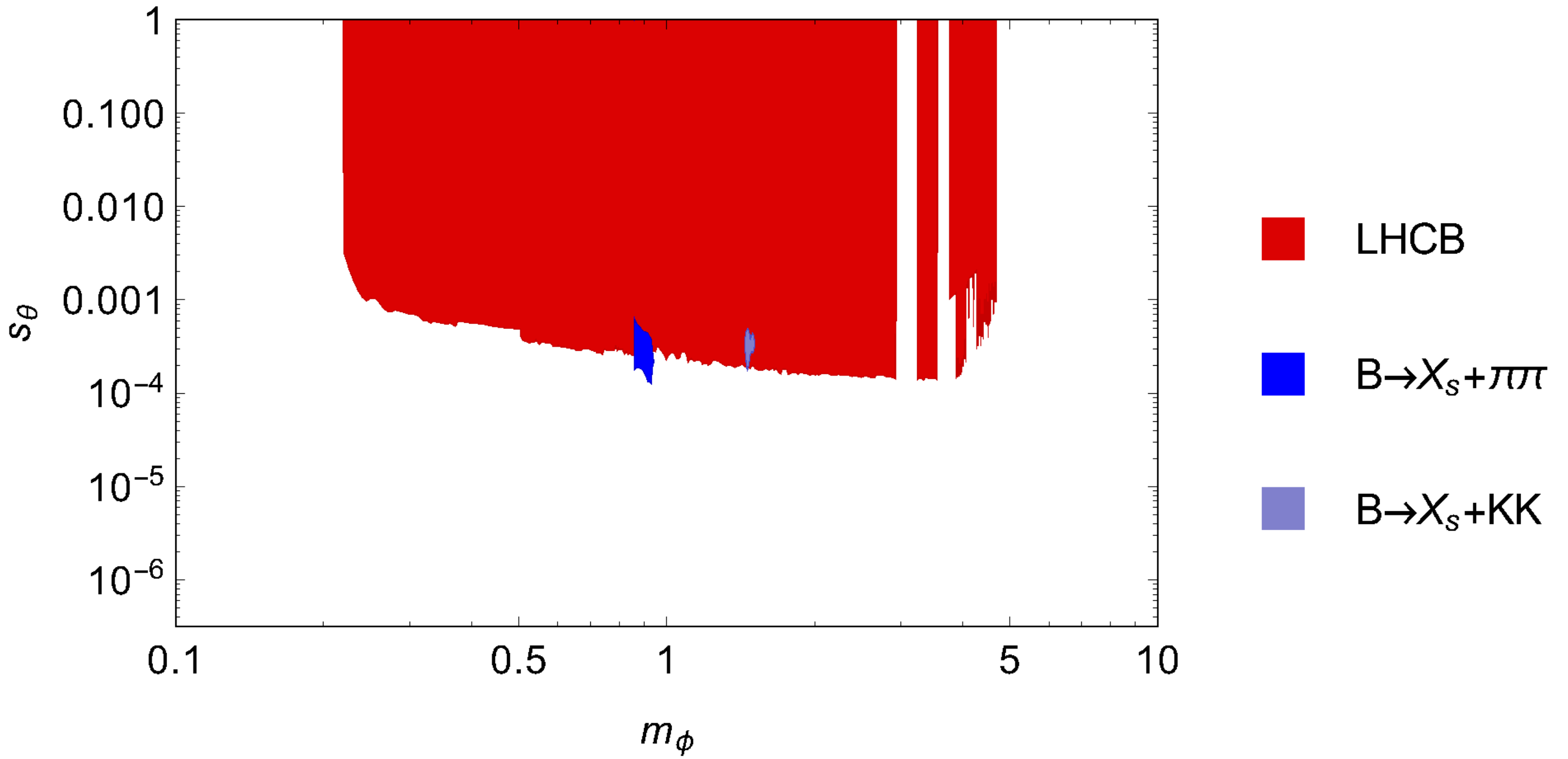


Displaced Vertices

- new searches for B decays to long-lived boson

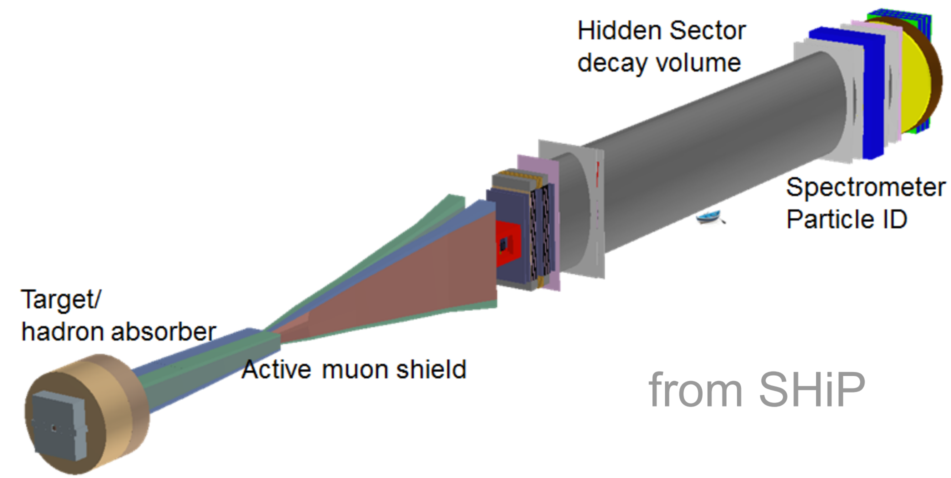
$B \to K^{(*)}\mu\mu$ (LHCB) $B \to X_s\ \pi\pi, KK$ (BaBar)

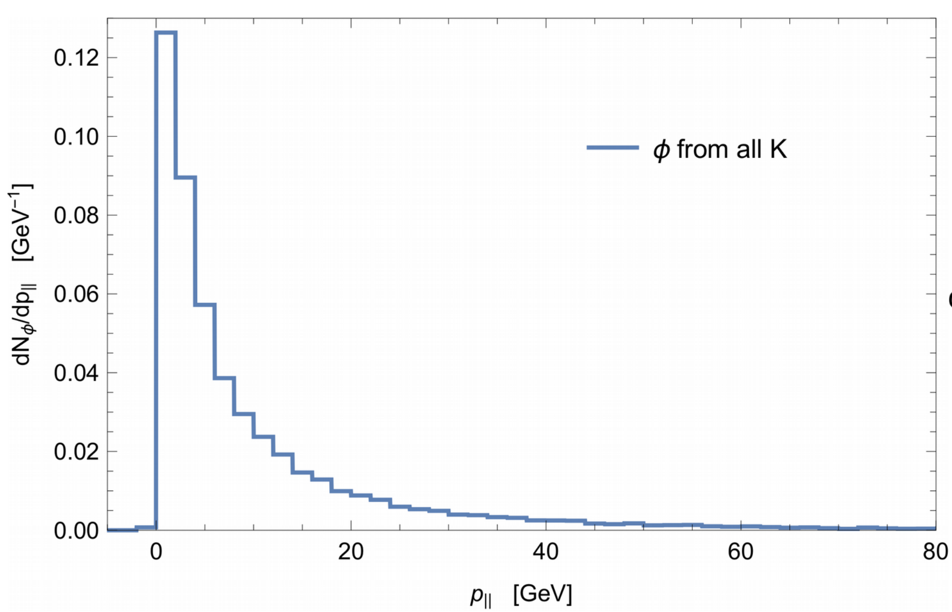
Phys.Rev.Lett. 115 (2015), Phys.Rev. D95 (2017) Phys. Rev. Lett. 114 (2015)

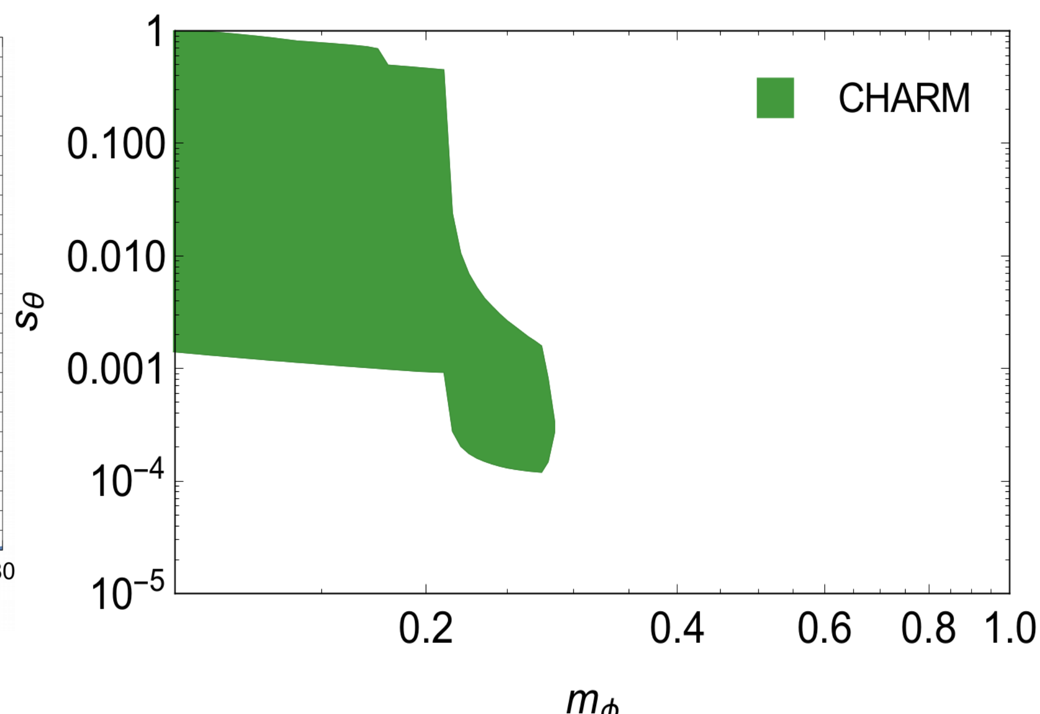


Beam Dumps

- strongly displaced vertices testable at beam dumps
- example: CHARM
  Phys.Lett. 157B (1985)
- simulation with Pythia

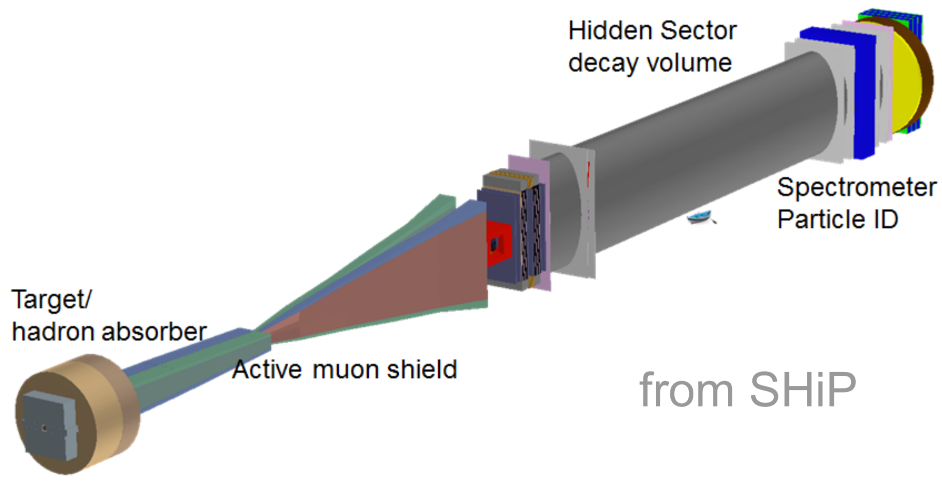


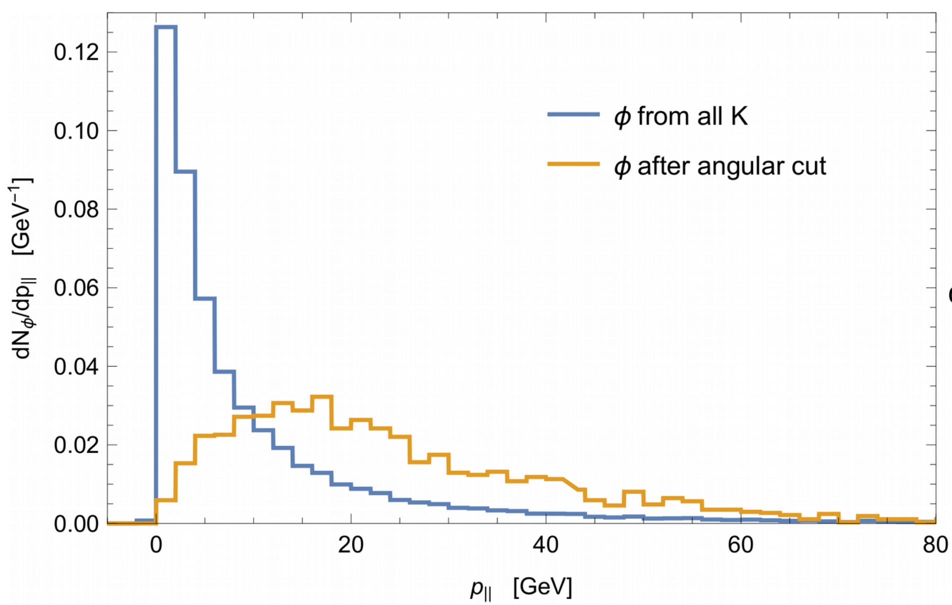


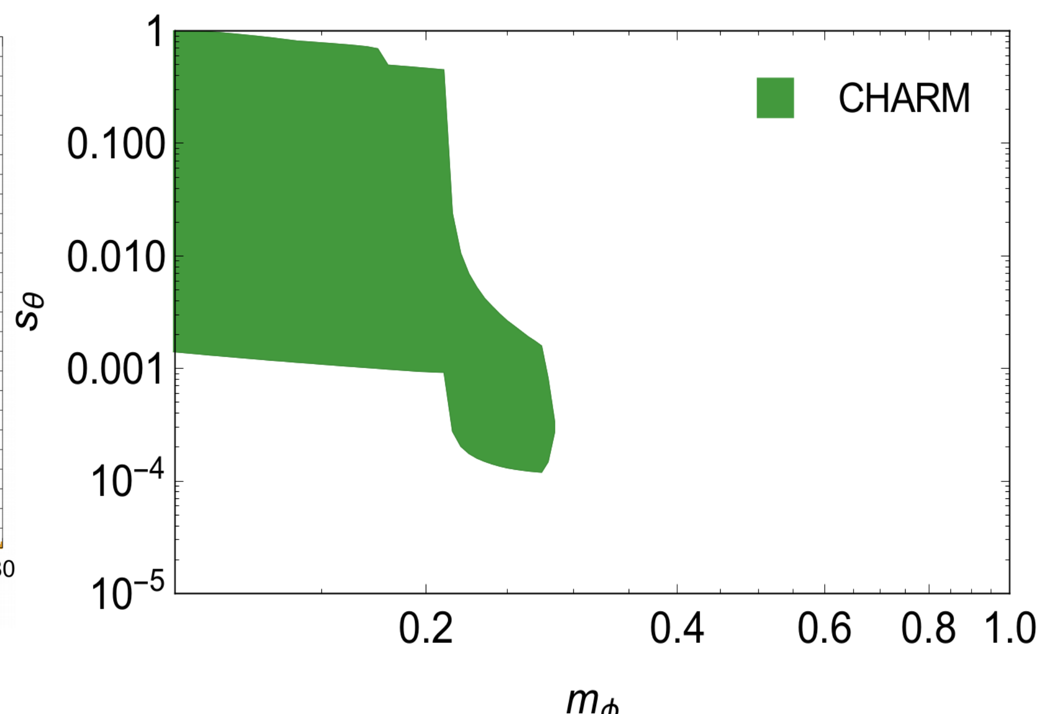


Beam Dumps

- strongly displaced vertices testable at beam dumps
- example: CHARM
  Phys.Lett. 157B (1985)
- simulation with Pythia

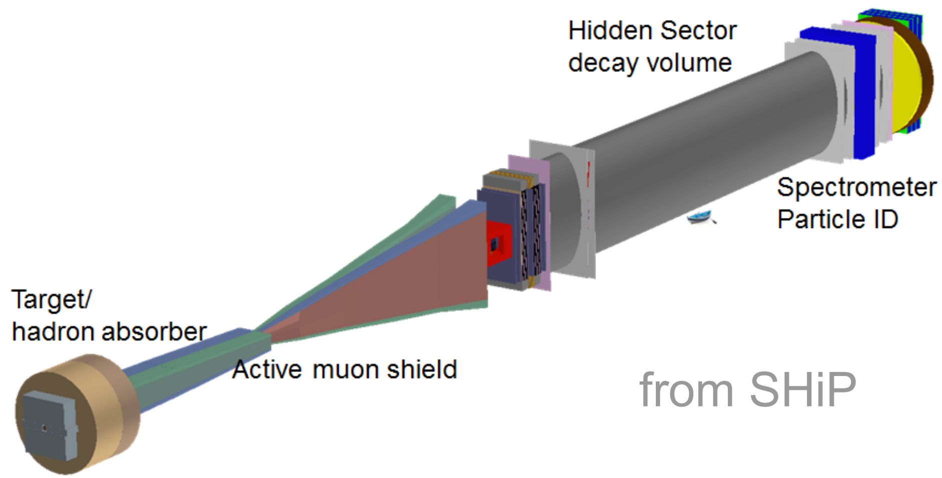


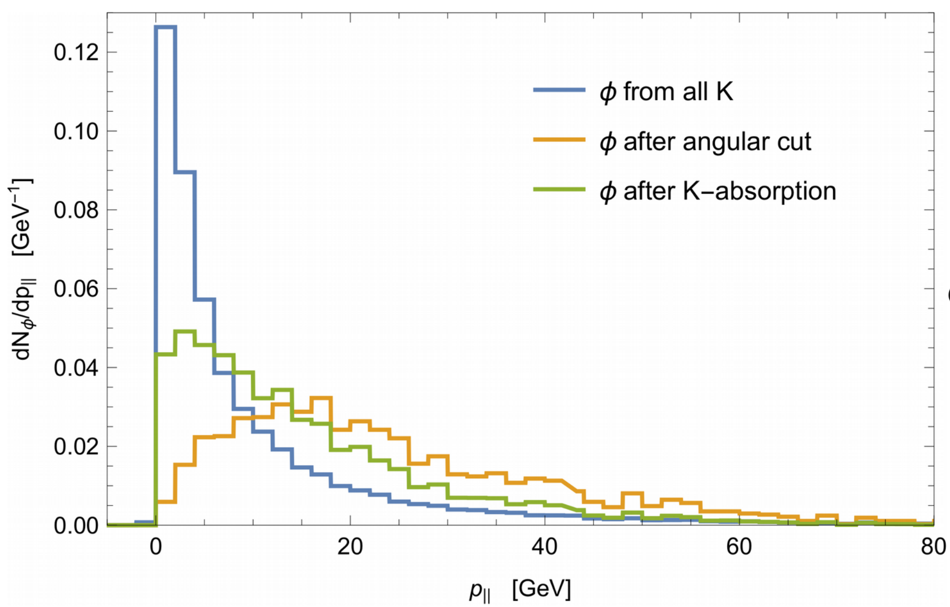


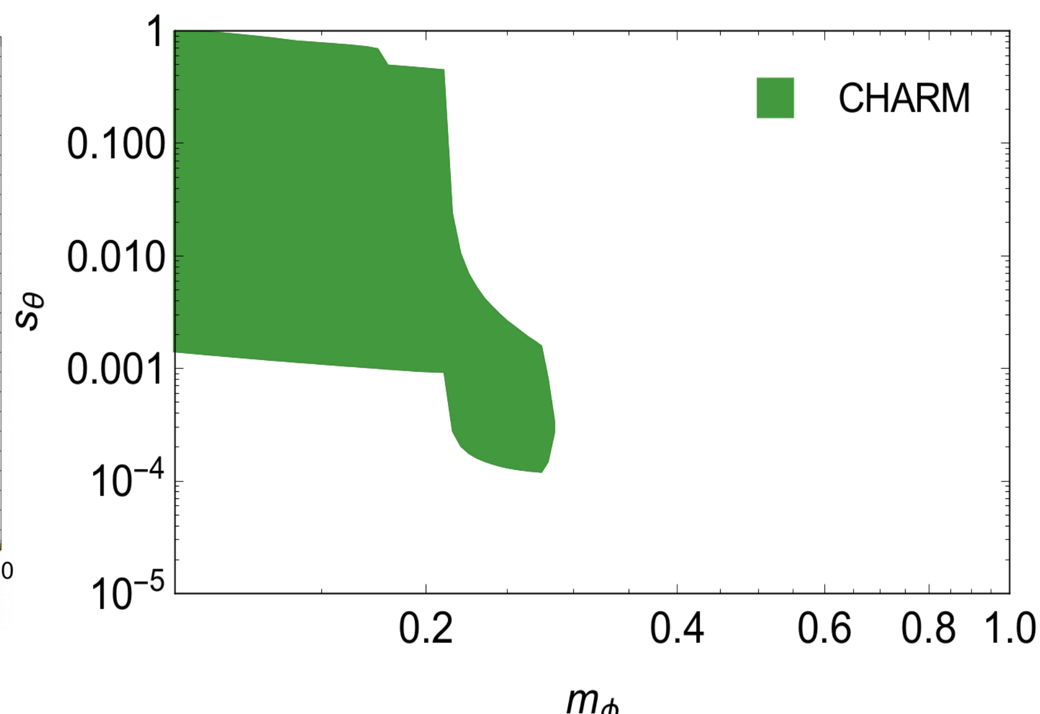


Beam Dumps

- strongly displaced vertices testable at beam dumps
- example: CHARM
  Phys.Lett. 157B (1985)
- simulation with Pythia

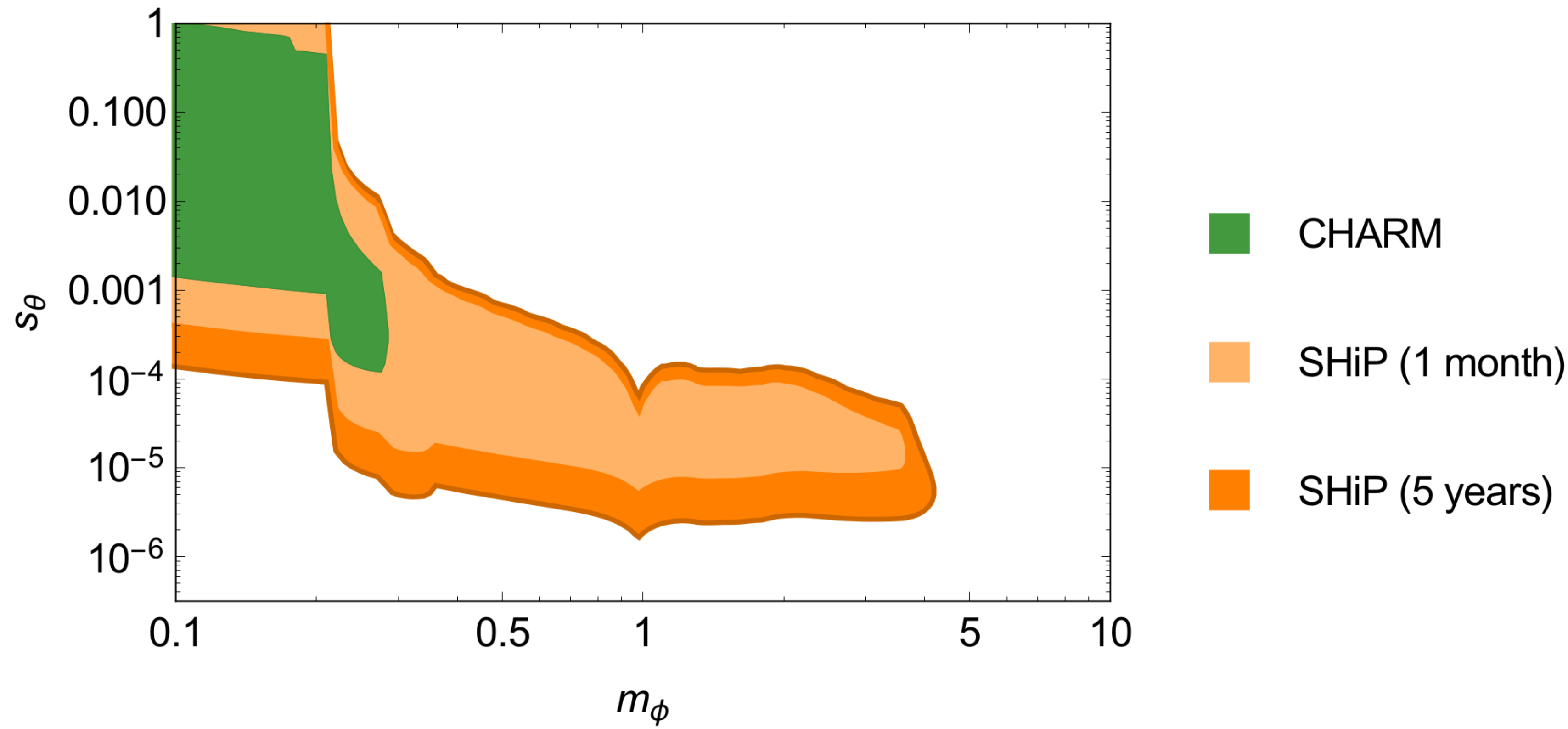






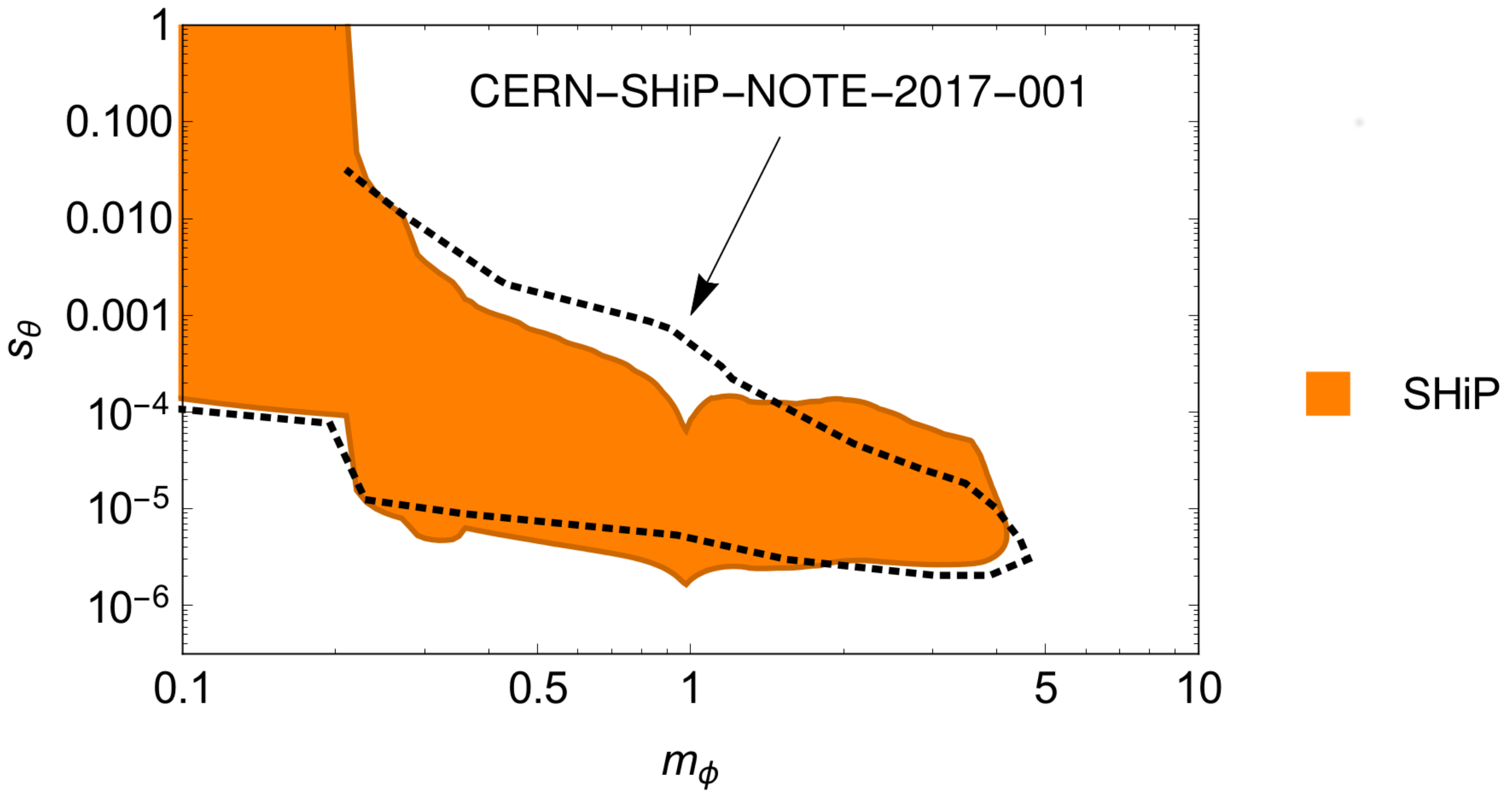
CHARM vs. SHiP

	N_{POT}	E_P	Decay Region	Geom. Coverage
CHARM	2×10^{18}	400 GeV	480 - 515 m	~0.3 - 1 % (B) ~0.1 - 0.2 % (K)
SHIP	2×10^{20}	400 GeV	69 - 120 m	~20 - 80 % (B) ~5 - 20 % (K)



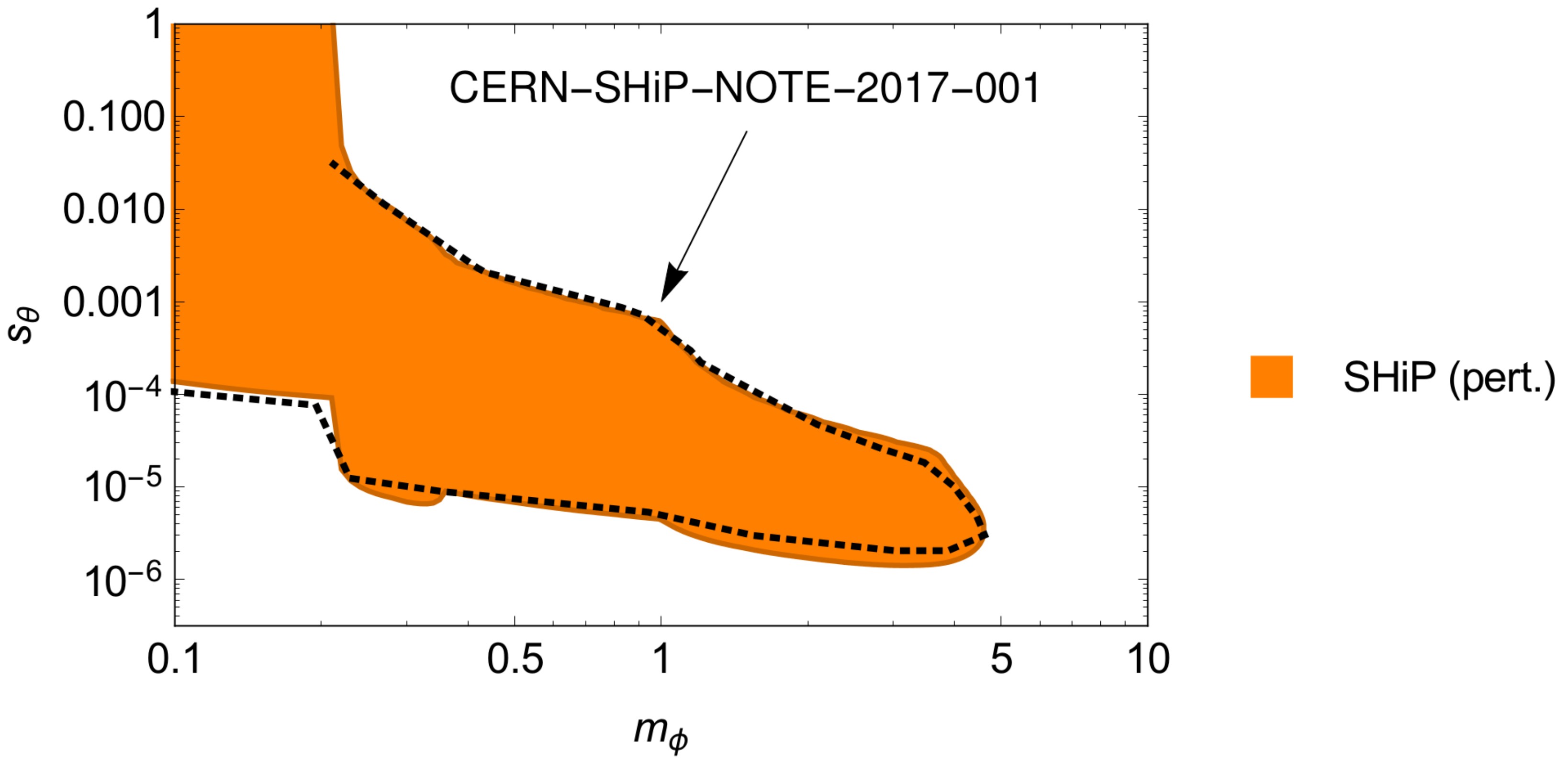
CHARM vs. SHiP

	N_{POT}	E_P	Decay Region	Geom. Coverage
CHARM	2×10^{18}	400 GeV	480 - 515 m	~0.3 - 1 % (B) ~0.1 - 0.2 % (K)
SHIP	2×10^{20}	400 GeV	69 - 120 m	~20 - 80 % (B) ~5 - 20 % (K)



CHARM vs. SHiP

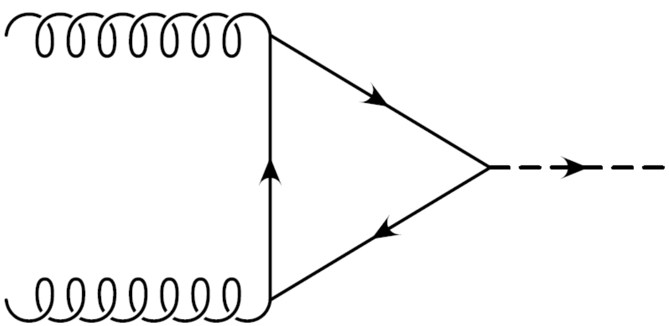
	N_{POT}	E_P	Decay Region	Geom. Coverage
CHARM	2 x 10^{18}	400 GeV	480 - 515 m	~0.3 - 1 % (B) ~0.1 - 0.2 % (K)
SHIP	2 x 10^{20}	400 GeV	69 - 120 m	~20 - 80 % (B) ~5 - 20 % (K)



Incomplete List of further Constraints

- LEP Higgs Searches
  L3, Phys.Lett. B385 (1996), OPAL Eur.Phys.J. C27 (2003)

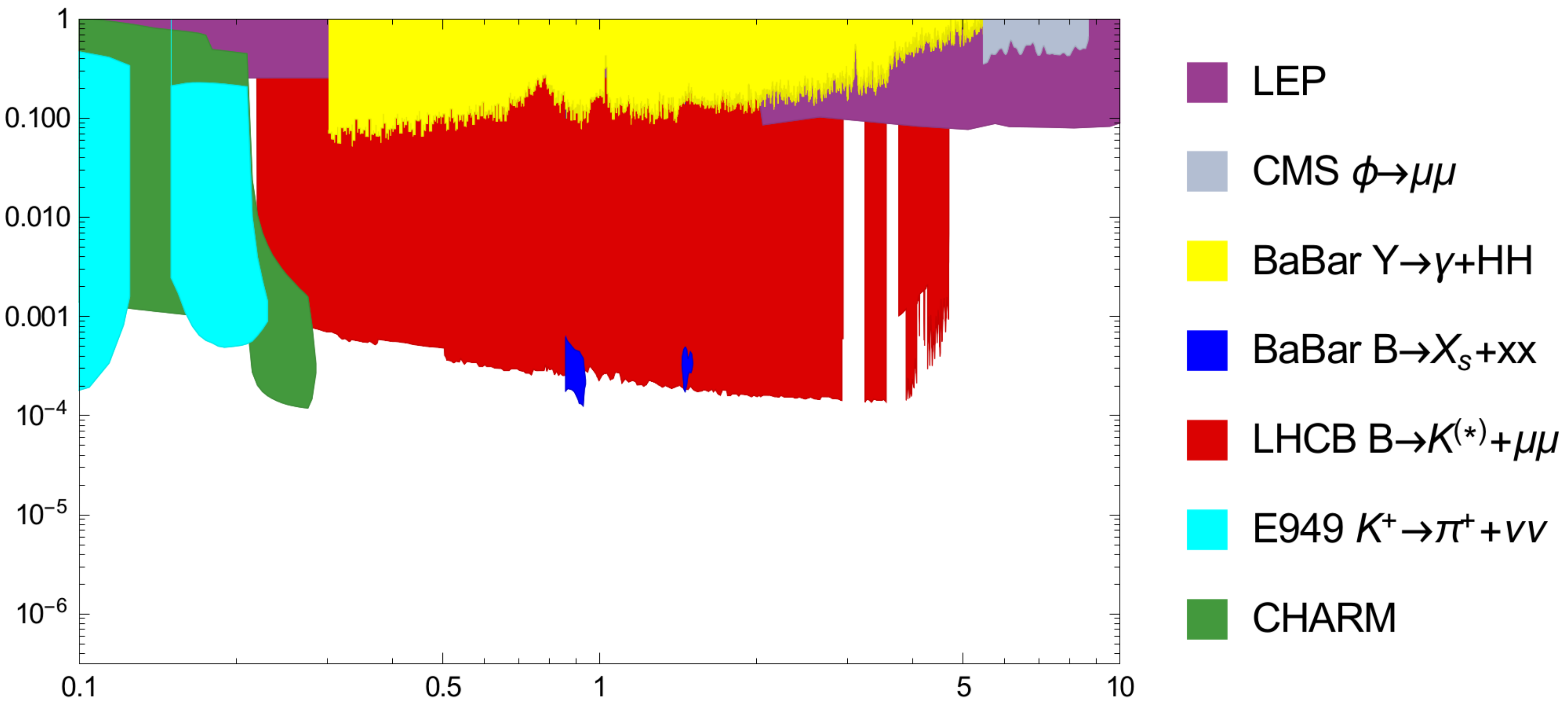
- LHC light Higgs search (μμ channel)
  CMS, Phys. Rev. Lett. 109 (2012)



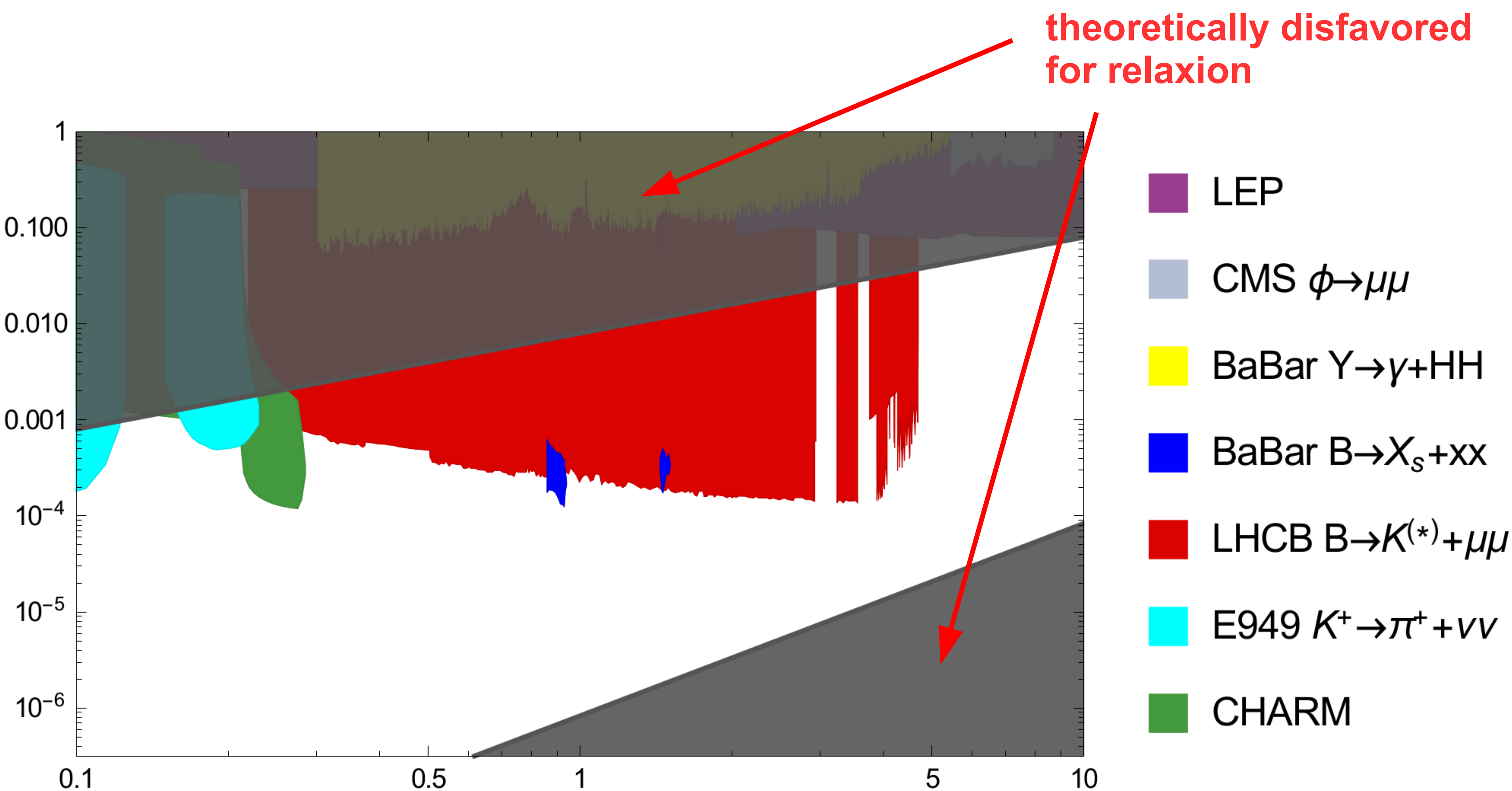
- $K \to \pi\nu\nu$, $\pi\mu\mu$
  E949, Phys.Rev. D79 (2009)

- $\Upsilon \to \gamma$ + hadrons
  BABAR, Phys.Rev.Lett. 107 (2011)

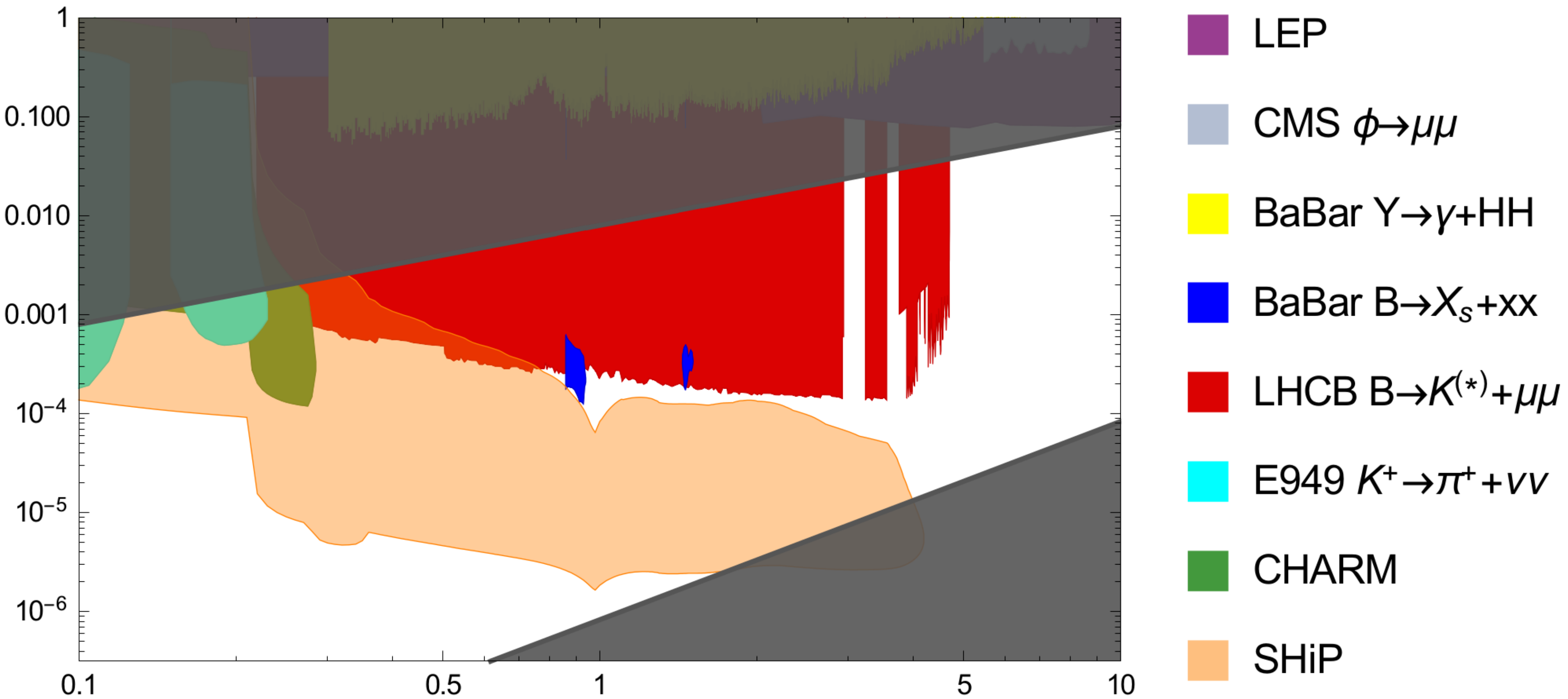
Summary Plot



Summary Plot



Summary Plot



Conclusion

- light scalar ($m_\phi = 0.1$-10 GeV) constitutes simple, well-motivated and predictive extension of the standard model
- uncertainties in its decay reduced to $O(1)$ through pion phase shift analysis
- rare meson decays (with displaced vertices) provide the most sensitive probe